

Numerical Simulation of Analysis on Erosion Failure of Right-angle Elbow Pipe

Dong Liang, Rui Jiang, Longlong Guo, Hongwei Li

Abstract—With widespread application of Oil-gas Mixing Transportation, the failure phenomenon caused by corrosion and erosion generally appears in the elbow region of gathering pipelines. The paper utilizes CFD Method and CFX Software to analyze flow field and stress of direct elbow pipe and respectively explore the influences of gaseous and liquid phases on erosion failure of elbow region. As the research shown, the turbulence prediction generated by a large number of liquid phases flowing past outer arch wall surfaces of elbow pipe affected by centrifugal force is the main research for erosion failure firstly occurred in arch walls, and meanwhile, secondary flow phenomenon generated by gaseous phase extends the distribution scope of erosion failure in walls of downstream pipes of elbow region. In addition, although the shear stress in wall is quite small, it plays a promotion role in exfoliation of corrosion product film in pipe wall in order to speed up the failure. Fluid erosion destroys corrosion product film in wall and aggravates its exfoliation, which is the reason for elbow failure.

Index Terms—Elbow; Gaseous Phase; Liquid Phase; Numerical Simulation; Flow Field & Stress Analysis

I. INTRODUCTION

In the pipeline system, erosion failure is one of main forms for pipeline failure. Since in the oil-gas gathering and transferring process, natural gas, gas condensate and corrosive substances are often mixed in the pipelines, by the mixture effect, it is very easy for right-angle elbow pipe to be eroded by fluid media to cause failure. Experiment is the traditional method to research erosion failure of pipe fittings. However, due to its shortcomings of long cycle of operation and high cost, numerical method is often adopted for its qualitative analysis. The paper utilizes CFX Software for numerical simulation. Compared with other fluid numerical simulation software, CFX has a certain amount of advantages of precise numerical calculation, quick computational solution and abundant physical models.

II. ESTABLISHMENT OF MODEL

A. Physical Model

Taking right-angle elbow pipe of oil-gas gathering and transferring pipeline system as the case (Fig.1), the drift diameter of elbow pipe is 100mm with bending diameter ratio of 1.5, the length of 850mm from inlet to elbow and the length of 650mm from elbow to outlet. The right-angle elbow pipe is placed horizontally where positive direction of Z axis is represented as gravity direction; negative direction of X axis

is as inlet direction; and positive direction of Y axis is as outlet direction.

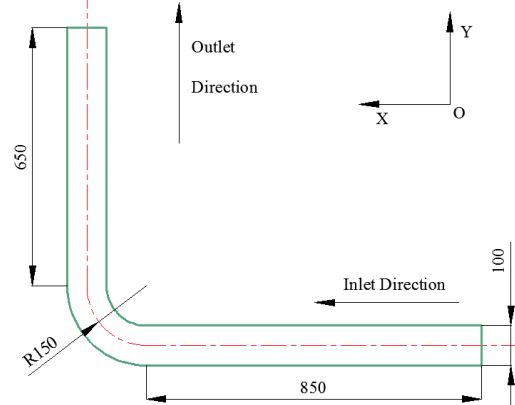


Fig.1 Geometric model of fluid domain of right-angle elbow pipe

B. Mathematical Model

Fluid flow in right-angle elbow pipe is a complicated multiphase three-dimensional flow process and its movement equation can be deduced from Law of Conservation of Mass and Law of Conservation of Momentum [1].

Law of Conservation of Mass:

$$\frac{\partial}{\partial t}(\rho_m) + \nabla \cdot (\rho_m \vec{v}_m) = \dot{m} \quad (1)$$

Law of Conservation of Momentum:

$$\frac{\partial}{\partial t}(\rho_m \vec{v}_m) + \nabla \cdot (\rho_m \vec{v}_m \vec{v}_m) = -\nabla p + \nabla \cdot [\mu_m (\nabla \vec{v}_m + \nabla \vec{v}_m^T)] + \rho_m \vec{g} + \vec{F} + \nabla \cdot \left(\sum_{k=1}^n \alpha_k \rho_k \vec{v}_{dr,k} \vec{v}_{dr,k} \right) \quad (2)$$

Law of Conservation of Energy:

$$\frac{\partial}{\partial t} \sum_{k=1}^n (\alpha_k \rho_k E_k) + \nabla \cdot \sum_{k=1}^n [\alpha_k \vec{v}_k (\rho_k E_k + p)] = \nabla \cdot (K_{eff} \nabla T) \quad (3)$$

In the formula: ρ_m is represented as mixture density, kg/m^3 ; \vec{m} as average mass velocity, m/s ; \dot{m} as source item of quality; p as fluid pressure, pa ; α_k as volume fraction of k-phase medium; $\vec{v}_{dr,k}$ as drift velocity of k-phase medium, m/s ; μ_m as mixed viscosity, $pa \cdot s$; \vec{F} as body force, N ; E_k as kinetic energy of k-phase fluid, J and k_{eff} as effective thermal conductivity, $W/(m \cdot K)$.

Kinetic Energy Equation of Turbulent Fluctuation (K Equation):

$$\rho \frac{\partial K}{\partial t} + \rho \mu_i \frac{\partial K}{\partial x_i} = \frac{\partial}{\partial x_j} \left[\left(\mu + \frac{\mu_t}{\sigma_K} \right) \frac{\partial K}{\partial x_j} \right] + G_K + G_b - \rho \varepsilon - Y_m \quad (4)$$

Dissipation Equation of Turbulent Kinetic Energy (ε Equation):

$$\rho \frac{\partial \varepsilon}{\partial t} + \rho \mu_i \frac{\partial \varepsilon}{\partial x_i} = \frac{\partial}{\partial x_j} \left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon} \right) \frac{\partial \varepsilon}{\partial x_j} \right] + \frac{C_{1\varepsilon} \cdot \varepsilon}{K} (G_K + C_{3\varepsilon} G_b) - C_{2\varepsilon} \rho \frac{\varepsilon^2}{K} \quad (5)$$

$$\mu_t = C_\mu \rho \frac{K^2}{\varepsilon}$$

In the formula: G_k is represented as generation item of turbulence energy caused by average velocity gradient; G_b as generation item of turbulence energy caused by buoyancy; Y_m as pulse expansion contribution in compressible flow; μ_t as turbulence viscosity, $pa \cdot s$; μ_i and μ_j as time-averaged velocity, m/s ; K as turbulent kinetic energy, J ; ε as turbulent dissipation rate; ρ as fluid density, kg/m^3 ; σ_K and σ_ε as turbulent prandtl value of K and ε equations; $C_{1\varepsilon} = 1.44$, $C_{2\varepsilon} = 1.92$, $C_{3\varepsilon} = 1$ and $C_\mu = 0.09$ as empirical constants.

III. NUMERICAL SIMULATION

CFX is applied to simulate flow of fluid in right-angle elbow pipe and the data collected on the site is set as boundary condition. It is specific that: gaseous phase is set as continuous fluid and liquid phase as discrete fluid [2], and meanwhile gravity effect is considered. Mass flow rates and volume fractions of gaseous and liquid phases are set as inlet boundary conditions, while static pressure of average cross section is as outlet boundary condition. The gridding is partitioned as follows:

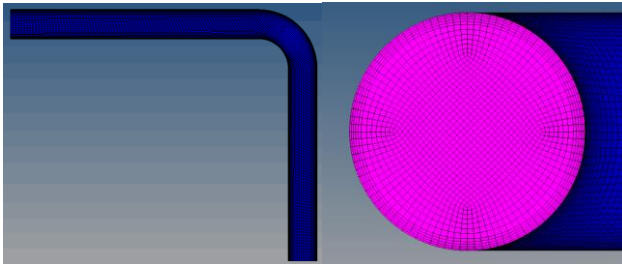


Fig.2 Gridding model of fluid domain of right-angle elbow pipe

Steady-state Simulation and Finite Volume Method are adopted to implement numerical simulation for flow in the comprehensively developed gaseous- and liquid-phase flow pipes in order to get velocity field contour and velocity vector diagram of flowing medium, volume fraction contour of downstream section in liquid-phase elbow as well as pressure contour and shear stress contour of pipe wall.

IV. NUMERICAL SIMULATION RESULT AND ANALYSIS

A. Velocity and Volume Distribution

Four sections are removed in elbow region and its downstream area, as shown in Fig.3.

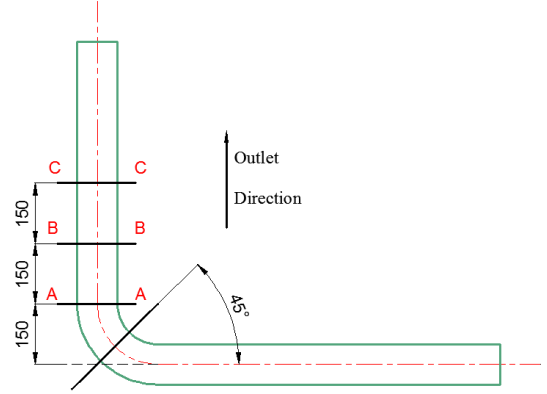


Fig.3 Schematic diagram of section location

The streamline is composed of different fluid particles, which gives the direction of motion of different fluid particles at the same time. The volume fraction of the section can reflect the proportional relation of the material at a certain time.

Streamline diagrams of gaseous and liquid phases in elbow section of elbow pipe are as shown in Fig.4 and 5. Liquid-phase volume fraction contours are represented in four sections, as shown in Fig.6 and 7.

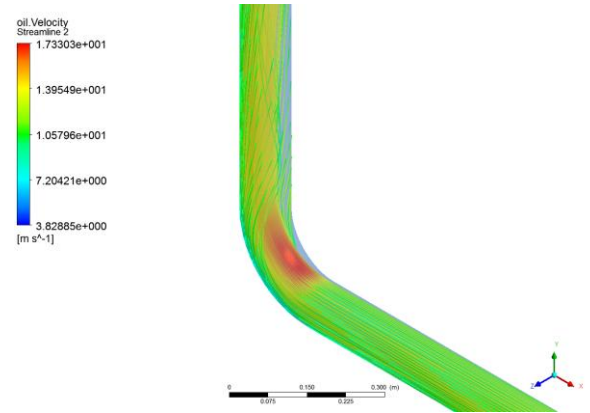


Fig.4 Liquid-phase streamline diagram

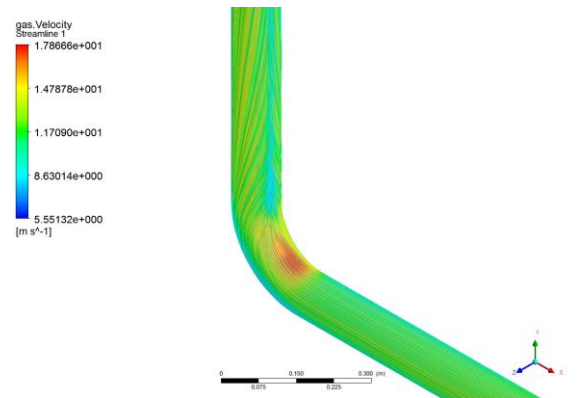


Fig.5 Gas-phase streamline diagram

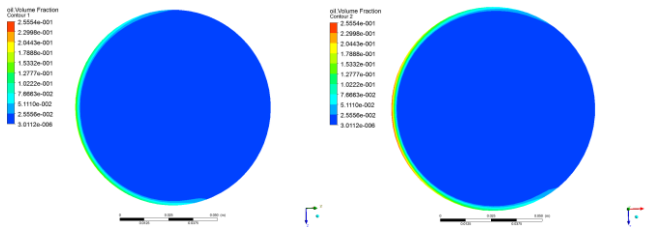


Fig.6 Liquid-phase volume fraction contour of 45° elbow (l) and A section (r)

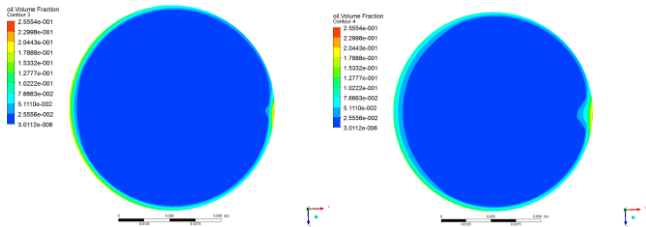


Fig.7 Liquid-phase volume fraction contour of B (l) and C (r) section

When stationary flow, the speed of the fluid particle in the flow field does not change over time, so the same point of streamline shape always remain the same. But in unsteady flow, its outcome has totally different.

From the streamline contour, when the fluid doesn't enter the elbow section, its flow is smooth and steady, and meanwhile gaseous and liquid phases are uniformly distributed. When the fluid flows past the elbow section, its flow is changed sharply. In addition, the fluid velocity near the interior wall of elbow pipe is significantly faster than that of exterior wall. At the moment, the maximum speed of gaseous phase is much quicker than that of liquid phase, respectively namely, 17.87m/s and 17.33m/s.

From the liquid-phase volume fraction contour, it is shown liquid phases are intensively distributed in the exterior wall of the elbow and its neighboring downstream region. It is because: when elbow is flowed through, since discrete liquid-phase particle mass is relatively larger than that of continuous gaseous phases, the flow is hard to be rapidly changed with elbow curvature so that it can only hit against exterior wall of elbow by a certain angle of incidence, thus liquid phases are largely distributed in exterior walls, while gaseous phases can be well full of the whole fluid domain. However, because it is the interior wall in right-angle elbow region, the direction of fluid velocity is not completed immediately. No matter liquid or gaseous phases, they both have the flow trend to break away from interior wall to a certain extent.

The fluid erodes increasingly the wall of elbow pipe without rules, which aggravates the exfoliation of corrosion product film and promote the failure of pipes [3]. From volume fraction contour, it is seen a large number of liquid phases are flowed through exterior wall of downstream section in elbow pipe and it is in the region that actual failure of elbow pipe is appeared. Thus, liquid phase is the main reason for erosion failure of elbow pipe.

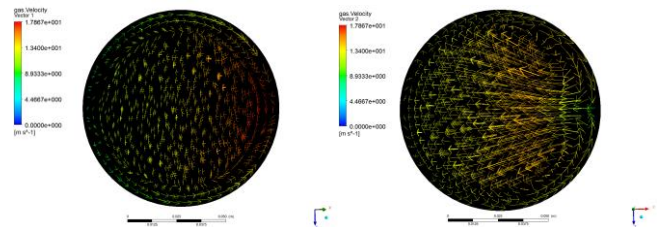


Fig.8 Gas-phase velocity vector diagram of 45° elbow (l) and A (r) section

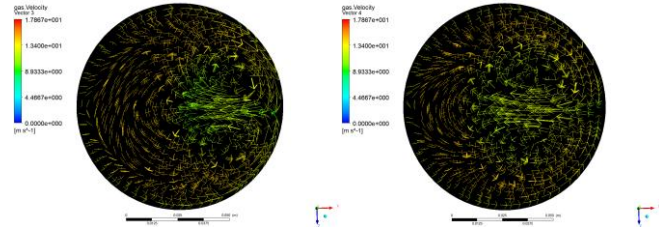


Fig.9 Gas-phase velocity vector diagram of B (l) and C (r) section

When flowing through elbow pipe, fluid's turbulence intensity is aggravated obviously, which is kept for some distance. The vector diagrams for velocity of gas in sections are as shown in Fig.8 and 9. According to velocity distribution of all sections, velocity vectors of different sections are distinctly changed, especially in velocity direction. It can be seen from velocity vectors of four sections that the secondary flow phenomenon is generated by fluid with the circle from exterior wall, though interior wall and central region of section finally back to exterior wall [4].

Due to high volume fraction and relatively uniform distribution in pipeline, gaseous phases have the obvious secondary flow phenomenon, while since liquid phase is mainly distributed in pipe wall, its secondary flow phenomenon is quite weak.

Secondary flow is in the strongest status when in elbow region, but it is increasingly weakened until disappearance after fluid leaves elbow pipe and it extends the erosion range of fluid on pipe wall and influences the distribution of failure area.

B. Pressure Distribution

Wall pressure contours for elbow pipes are as shown in Fig. 10 and 11.

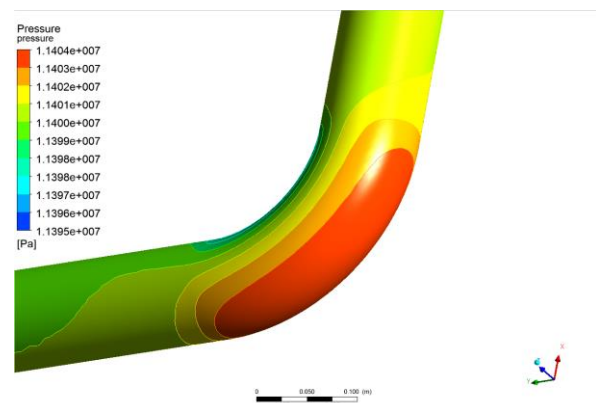


Fig.10 Pressure contour of exterior wall of elbow region

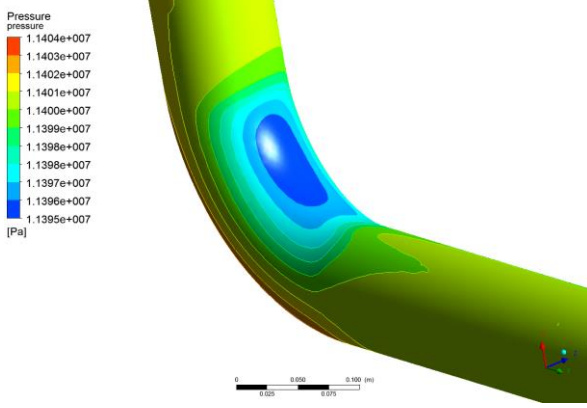


Fig.11 Pressure contour of interior wall of elbow region

From the Fig. above, it is shown pressure distribution is opposite to that of velocity. It is the low pressure area near interior walls in elbow region and high pressure area near its exterior walls. In addition, high pressure area is quite thick, while low area is relatively thin.

The different pressure areas have obvious lamination. It is mainly because: when fluid flowing through elbow region, affected by centrifugal force, a large number of fluids hit continuously against exterior walls by a certain angle of incidence, but have less influences on interior walls and even some fluids bypass the interior walls, thus the effect degree by fluids on interior walls is weaker than that on inflow straight pipe, which causes interior wall becomes the area with the lowest pressure.

In the process of interaction by fluid and wall, velocity direction is changed with reduced speed rate. Since elbow pipe is placed horizontally, potential energy of fluid in all points of pipe is broadly similar. Therefore, it is seen when fluid flows through elbow region, pressure energy transformed by lost kinetic energy cause exterior wall is in high-pressure status compared with interior one.

Pressure reflects the impact strength of fluid particles on pipe wall. The more pressure is, the easier the corrosion product film of pipe will be exfoliated and thus elbow pipe will be failed. Therefore, failure in exterior wall of pipe is prior to that in interior wall.

In downstream area of elbow outlet, because of inertia effect, the fluid that just leaves elbow pipe won't immediately be recovered to the original flowing status in straight pipe so that the pressure of exterior wall in downstream pipe near elbow outlet is still higher that of interior wall. And with continuous development of flowing, the pressure will be gradually restored to the progressively decreased status along axis line of straight pipe.

C. Shear Stress of Wall Surface

Traditional fluid mechanics in dealing with the problem of fluid and wall think that near wall fluid micro layer adhered to the wall surface, when the relative slip occurs between the upper fluid and wall, a tangential stress is generated between the fluid layers. In this moment, wall will produce a stress to balance it in the opposite direction. The stress is called the wall shear stress.

Wall shear stress can intuitive reflect the reaction between fluid and pipe wall in the tangent direction along the wall. The distributions of maximum shear stresses of wall surfaces in gaseous and liquid phases are as shown in Fig. 12 and 13.

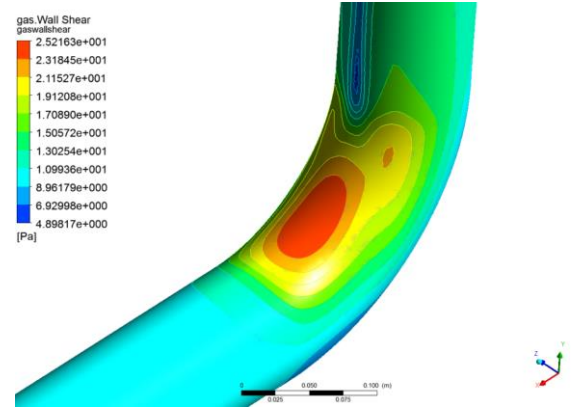


Fig.12 Shear stress contour of gas-phase wall surface

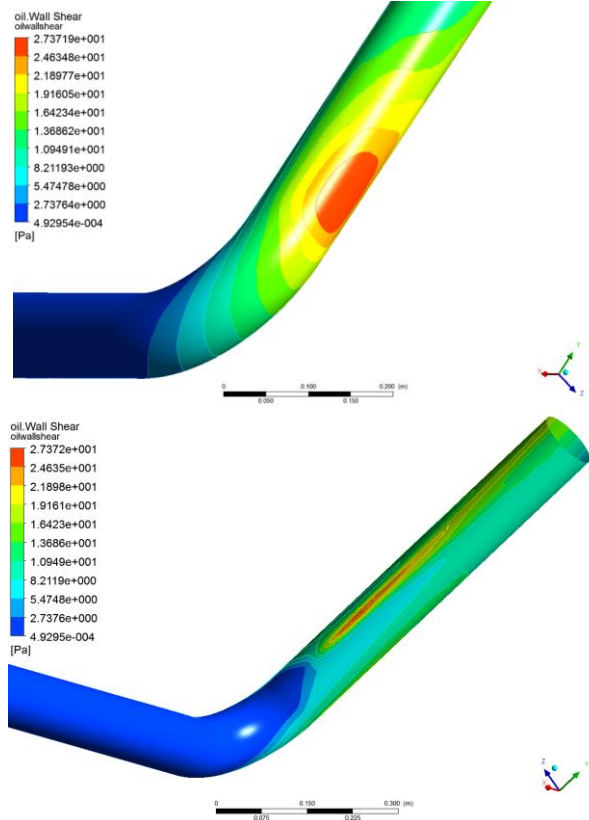


Fig.13 Shear stress contour of liquid-phase wall surface

Relatively large shear stress of liquid-phase wall surface is distributed in pipe walls on both sides of downstream region of elbow, especially distributed intensively in its outer wall surface since most of liquid phases are intensively distributed in outer arch wall surfaces due to the effect of centrifugal force and the shear stress of arch wall surface is increased by the interaction between concentrated liquid phase and exterior wall surface. In addition, because main flow along pipe axis is existed in pipes and closed secondary flow is appeared along radial direction of pipe section, some liquid phases flowed along outer arch wall surfaces are brought to inner arch wall in order to increase shear stress of inner arch wall surface.

Relatively large shear stress of gaseous-phase wall surface is intensively distributed in interior wall surface of elbow region. For gases, the loss of tangential momentum hitting against pipe wall is the main reason of shear stress generated in wall surface [5]. In arch wall of elbow region, velocity direction and speed rate of gases are changed in the most

furious degree in order to cause great losses of tangential momentum. Thus, inner arch wall is the place where shear stress of gaseous-phase high wall surface is concentrated.

The maximum shear stresses of liquid and gaseous phases are respectively 27.4pa and 25.2pa, and the maximum shear stress of liquid-phase wall surface is not larger than that of gaseous phase. For simulated working condition this time, liquid-phase volume fraction of pipe entrance is much smaller than that of gaseous phase, thus shear stress of wall surface caused by liquid phase shall play a dominant role.

V. CONCLUSION

- 1) When gaseous and liquid phases flow through elbow region, a certain gas-liquid separation phenomenon will be occurred due to effect of centrifugal force, thus liquid phases are much closer to exterior wall surface, while gaseous phases are uniformly distributed in other regions. And the secondary flow is existed in downstream region of elbow with coexistence of main flow. Turbulence prediction generated by concentrated distribution of a large number of liquid phases is the main reason for serious damages of exterior wall surface of elbow region.
- 2) In elbow region, low speed and high pressure are appeared in exterior wall surface, while high speed and low pressure are in interior one. In addition, shear stress of wall surface caused by liquid phases is relatively large. Although shear stress of wall surface is quite small in simulated working condition this time, it plays a promotion role in exfoliation of corrosion product film in pipe wall to accelerate failure of pipe wall to some extent.
- 3) Local turbulence has the obvious promotion effect on erosion and corrosion. In the part where turbulence is quite small, corrosion is in the dominant status, while erosion and corrosion are interacted mutually in the part with relatively large turbulence, which will further aggravate the failure of pipe fitting.
- 4) Gaseous and liquid phases are influenced by gravity. In particular, gravity has relatively larger effect on liquid phases, which results in the sedimentation phenomenon in flowing process to speed up the failure of bottom of pipe fittings.

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